Advanced Multi-Moment Microphysics for Precipitation and Tropical Cyclone Forecast Improvement within COAMPS

PI: Ming Xue
Center for Analysis and Prediction of Storms, University of Oklahoma
National Weather Center, Suite 2500
120 David Boren Blvd
Norman OK 73072, USA
Phone: (405) 325 6037 fax: (405) 3257614 email: mxue@ou.edu

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Co-PI: Fanyou Kong

LONG-TERM GOALS

The first major focus of this project is to implement and test an advanced microphysics package capable of predicting up to three moments (total number concentration, mass, and the 6th-moment reflectivity factor) of hydrometeor particle size distributions (PSDs) inside the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). The schemes will then be applied to the prediction of tropical cyclones (TC) and continental convective weather, with verification against detailed in-situ and remote-sensing observations.

The second major focus is to develop interface software to bring the COAMPS into the multi-model multi-physics storm-scale ensemble forecasting (SSEF) framework of CAPS (Xue et al. 2010), so that it can be run side by side with three other state-of-the-art mesoscale models (WRF-ARW, WRF-NMM and ARPS), in realtime, at 1 to 4 km resolutions, for continental-US (CONUS) sized domains. By using a common set of initial and boundary conditions, we will be able to identify the strengths, weaknesses and potential systematic biases of individual models, and understand the differences and commonalities of physics packages within these models and their performance. The findings will be used to guide the improvement to the COAMPS model. The framework will also be used to systematically test the performance of the multi-moment schemes implemented within COAMPS over a data-rich region.

OBJECTIVES

This project addresses important issues on severe weather forecasting model improvement, model verification, ensemble forecasting, and the understanding of TC predictability, all of which are of great interest to the Navy's research, development and operations. Improving TC forecasts through advanced data assimilation (DA) is also an extended goal. The research efforts serve to fill a number of R&D gaps of the Navy, DoD as well as NOAA's weather forecasting needs. In fact, it addresses our nation's priority need for significantly improved hurricane intensity forecast (NSB 2007). The research in general

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will accelerate our nation's capability in more accurately predicting highly-variable hurricane intensity, thereby potentially reducing hurricane-related losses through better preparedness and response, and reduction in the uncertainty in track and intensity forecasts that could directly translate into huge economic savings. The project will directly contribute to Navy's goal of reducing TC structure and intensity prediction error by 50% within a decade. The software developed within the Navy's COAMPS model framework has a direct path of transition to Navy's operations.

APPROACH

Being part of CAPS's multi-model ensemble system, COAMPS will be run during the Hazardous Weather Testbed (HWT, Weiss et al. 2010) Spring Experiment period, over the continental US domain, so as to take advantage of the vast volume of observational data that can provide accurate initial conditions and information for detailed verification. It will also allow us to leverage the NOAA-supported realtime storm-scale ensemble forecast experiments conducted by CAPS. We will also apply the multi-model ensemble system to selected TC cases, and evaluate the value and benefit of the multi-model ensemble system for improving the reliability and sharpness of TC probabilistic forecasting.

WORK COMPLETED

1. Implementation of multi-moment microphysics parameterization in COAMPS and testing for realtime continental convection forecasts

The multi-moment microphysics package based on the Milbrandt-Yau (2005a, 2005b) 2- and 3-moment schemes has been implemented within the COAMPS model, together with a simplified 2-moment version available in the WRF. The 2012 version was based on the publically version of COAMPS while the 2013 implementation was based on its latest research version.

2. Fall 2013 CAPS real-time TC forecasts using COAMPS

In fall 2013, CAPS continued to produce real-time TC forecasts for Atlantic and west Pacific basins. The forecasts were extended to 5 days, again at a 4 km grid spacing over large domains. Forecasts were also produced using COAMPS for typhoons Soulik and Usagi. This is the first time that COAMPS TC forecasts are produced at a convection-permitting resolution over a large domain without nesting. The track forecasts are compared to corresponding WRF forecasts, and to NRL's COAMPS real-time forecasts for the two typhoons, and significant differences were found.

3. 2012 Atlantic hurricane season real-time TC forecasts

Similar to 2010 (Xue et al. 2013), during the 2012 hurricane season, CAPS produced twice daily, 72 h single large domain (spanning 20-100W, 10-50N at the middle part of the domain) forecasts at 4 km grid spacing in real time for the Atlantic basin. Two sets of forecasts were produced using the operational EnKF-EnVar hybrid GFS analyses and the experimental global EnKF analyses produced by NOAA ESRL as the initial conditions, respectively. These experiments aim to examine the impact of grid res-

olution and initial conditions on hurricane forecasts. The forecast model used was WRF-ARW. The forecasts ran from August 1 through October 31 and covered named storms Ernesto through Tony. Forecast verifications were performed.

4. EnKF assimilation of satellite-derived winds and inner-core observations with Hurricane Earl (2010)

Rapid-scan satellite-derived winds, inner core airborne Doppler radar radial wind (Vr) and dropsonde observations are assimilated into WRF using CAPS's EnKF system for Hurricane Earl (2010) at a 4 km grid spacing. The individual and combined impacts of the above observations on the intensity and track forecasts with WRF model are examined. Part of the motivation is from the previous ONR Defense EPSCOR program (N00014-10-1-0133) synergistic with this ONR project. The investigation of DA impact allows us to better understand the TC prediction and predictability issues within the COAMPS model.

RESULTS:

1. Implementation of multi-moment microphysics in COAMPS and testing for realtime continental convection forecasts

The multi-moment microphysics implemented in COAMPS model were tested in the 2012 and 2013 CAPS Spring Forecast Experiment forecasts. The results are being analyzed and compared with the forecasts using the COAMPS default 1-moment microphysics scheme.

2. Fall 2013 CAPS real-time TC forecasts using COAMPS

For the 5-day real-time TC forecasts produced using WRF and COAMPS in fall 2013, GFS 0.5 degree analyses were used for initial conditions. The WRF model used the same configuration as CAPS's 2013 HWT Spring Experiment. The COAMPS configurations follow NRL's COAMPS-TC real-time forecast configurations, with Mellor-Yamada PBL, Liou-Fu radiation schemes and Rutledge and Hobbs (Rutledge; Hobbs 1983) single-moment microphysics. With the initialization package developed by CAPS, COAMPS is able to produce forecasts over a large domain (with more than 1000 by 1000 grid points), which is not supported by the original COAMPS initialization program.

The COAMPS forecasts of Soulik and Usagi are compared to WRF forecasts in Fig. 6 and Fig. 7. The large-scale circulation and rainband structures of WRF and COAMPS forecasts are generally consistent in both Soulik and Usagi cases. The rainbands in COAMPS forecasts are consistently stronger than WRF forecasts. In both cases, COAMPS appears to predict stronger intensities than WRF. WRF predicts large areas of rain-free eye regions while the eyes of COAMPS are more tightly wrapped in both cases. For Soulik, the MSLP of 5-day COAMPS forecast is 914 hPa, much stronger than the 930 hPa of WRF and the 950 hPa of best track. For Usagi, the MSLP of COAMPS forecast is 916 hPa, slightly stronger than the 920 hPa of best track and much better than the 935 hPa of WRF forecast. More analysis on the predicted vortex wind, temperature and rainband structure are ongoing. The two-moment Mil-

brandt-Yau microphysics parameterization implemented within COAMPS is also being tested for the COAMPS TC forecasts.

The COAMPS-predicted tracks from CAPS and NRL for Fitow and Usagi are compared in Fig. 8 (top panel). The CAPS COAMPS forecast shows significant improvement over NRL's forecast using multi-level nesting, suggesting a potential benefit of using single, large convection-permitting domain for TC track forecasting. Another forecast using the same large domain but a 36 km grid spacing was done for Fitow (Fig. 8, bottom panel). The tracks are very different in the high- and coarse-resolution forecasts. For this case where two typhoons existed in the domain, a small nested domains may not be able properly resolve both the inner core vortex structures and the surrounding circulations that can cause interactions between the two typhoons, leading to poor track forecasts. This issue will be investigated further.

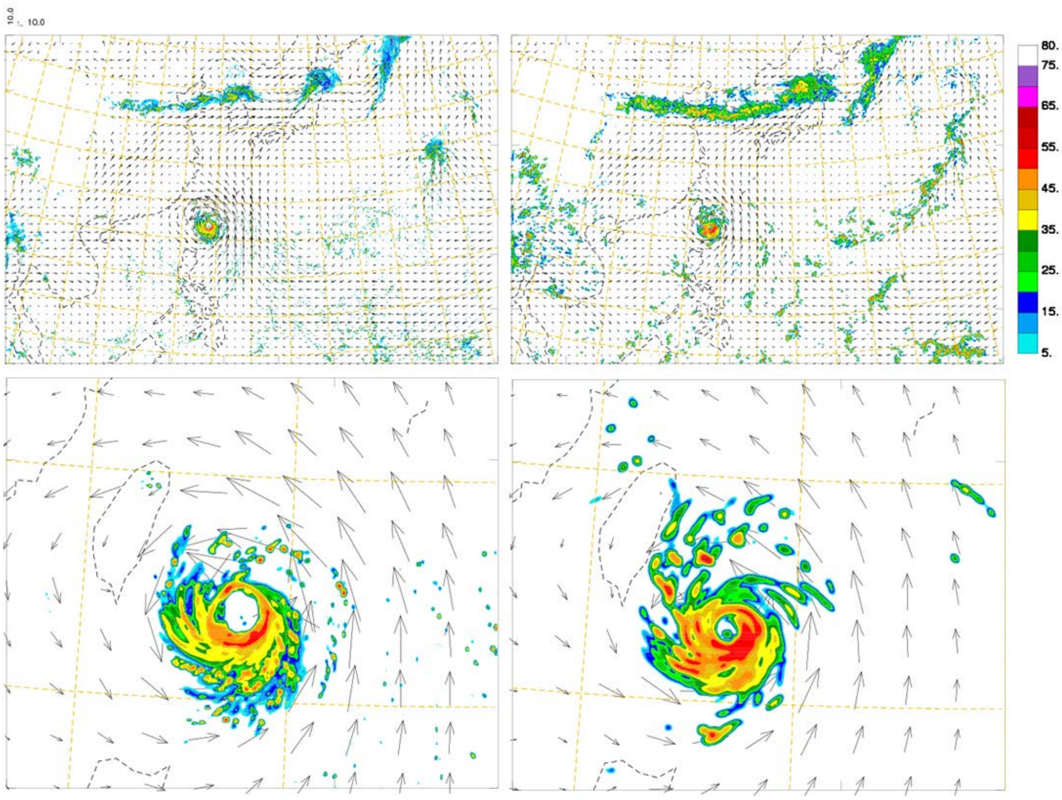

Fig. 1: 120-hour predicted reflectivity and wind at z=1.5 km for Typhoon Soulik valid at UTC 0000 July 12 2013 from WRF (left column) and COAMPS (right column).

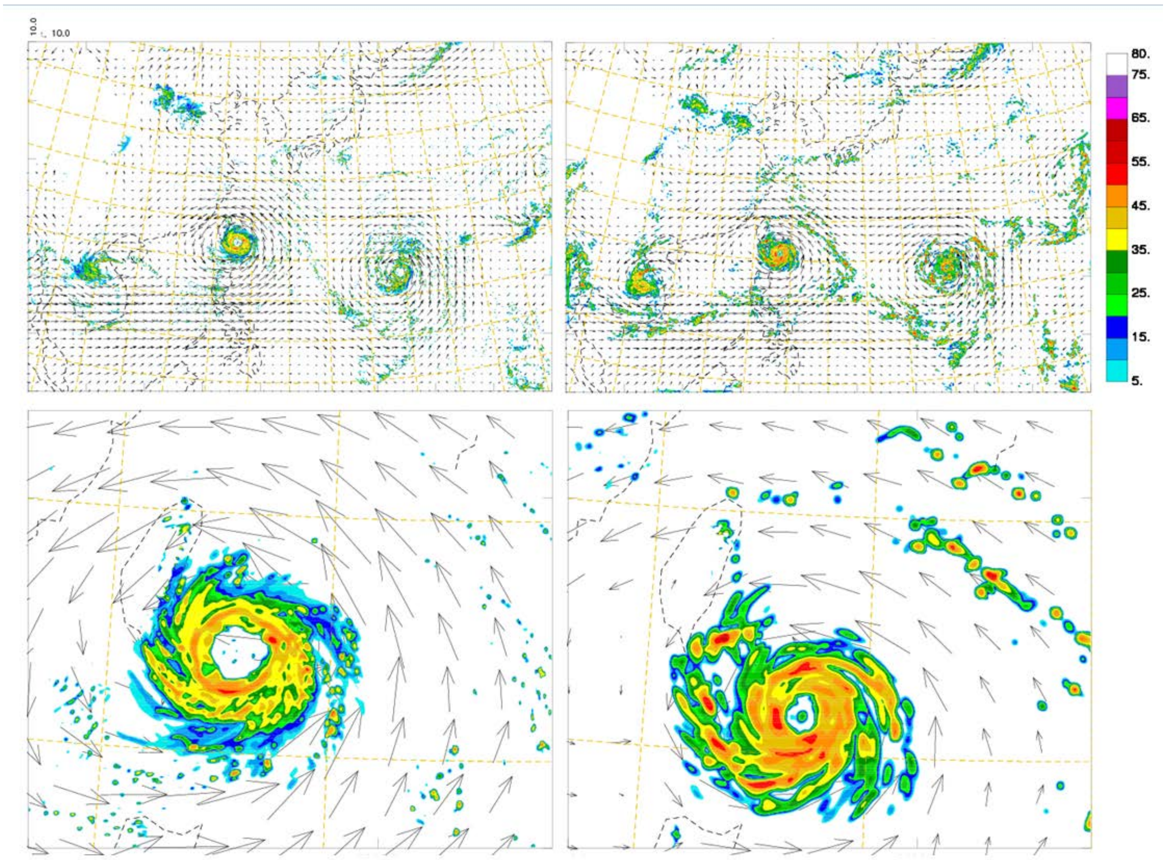

Fig. 2: 120-hour predicted reflectivity and wind at z=1.5 km for Typhoon Usagi valid at UTC 0000 September 21 2013 from WRF (left column) and COAMPS (right column).

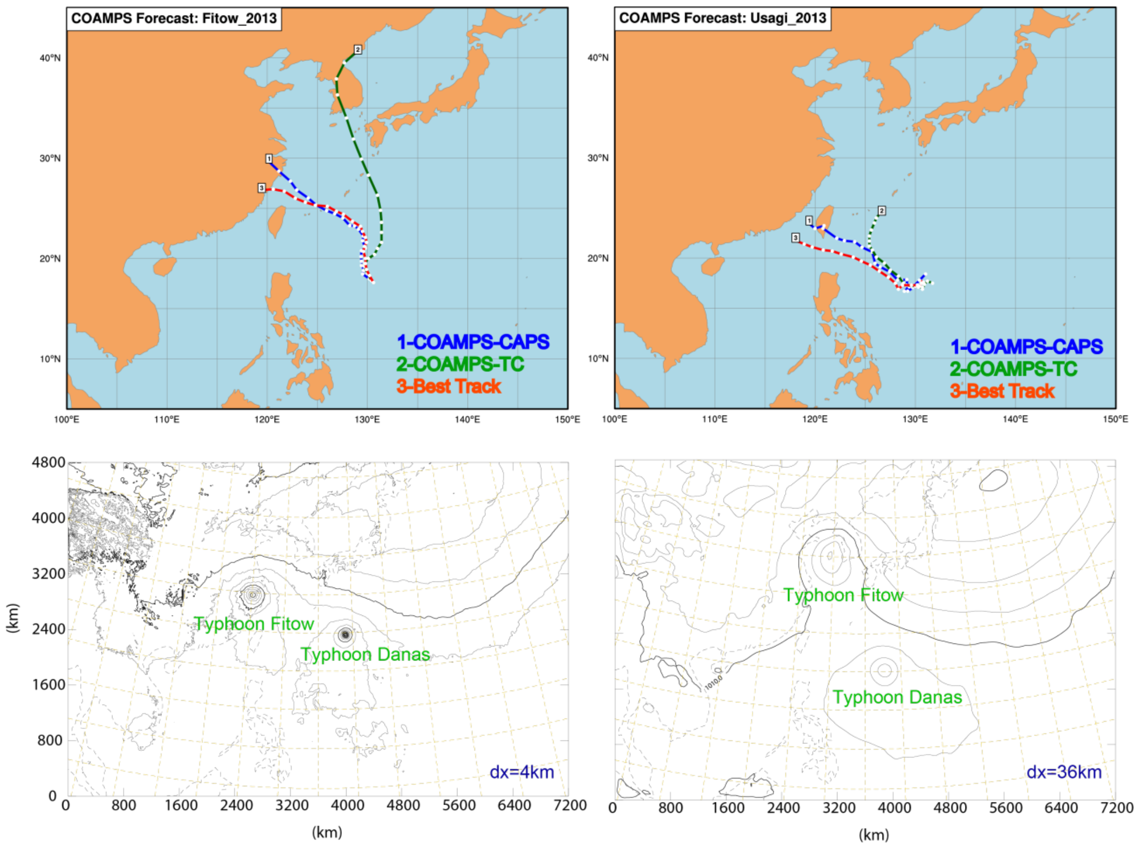

Fig. 3: Top panel: 5-day COAMPS track forecasts by CAPS and NRL for typhoon Fitow (top left; starting from 0000 UTC Sep. 17 2013) and typhoon Usagi (top right; starting from 0000 UTC Oct. 02 2013), along with the best track from Japan Meteorological Agency (JMA); Bottom panel: sea level pressure of 5-day COAMPS forecasts with a horizontal grid spacing of 4 km (bottom left) and 36 km (bottom right) for typhoon Fitow, valid at 0000 UTC Oct 7, 2013.

1. Verification of CAPS 2012 real-time Atlantic TC forecasts

Verification statistics were calculated against the best track data for the CAPS 2012 Atlantic hurricane season TC forecasts. For track forecasts (Fig. 1), the errors of EnKF-initialized forecasts are consistently larger than the hybrid-initialized forecasts for both GFS and WRF models, and the differences are larger earlier on. This indicates that the hybrid GFS analyses operationally implemented at NCEP since May 2012 are superior to the pure EnKF analyses. The WRF track errors are initially very close to the GFS forecasts initialized with the same ICs, but gradually grew larger than those of GFS. This result contradicts the 2010 results reported in Xue et al. (2013) where the high-resolution WRF produced smaller track error, although the forecasts were only 48 hour long.

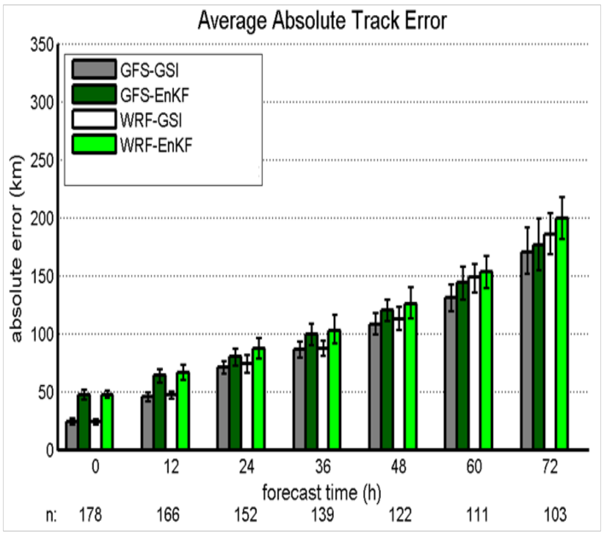

Fig. 4: Absolute track errors for Atlantic hurricane forecasts. Label GSI denotes GFS hybrid IC. Error bars represent the 90% confidence interval from bootstrap resampling. The number of forecasts is n.

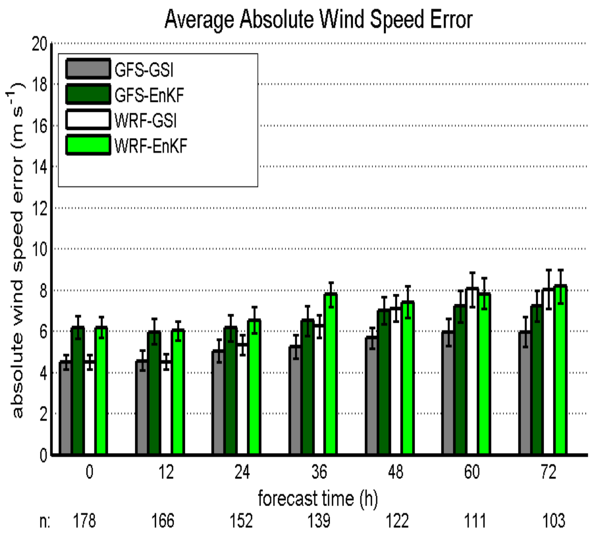

Fig. 5: Absolute 10 m wind speed error for Atlantic hurricane forecasts. Label GSI denotes GFS hybrid IC. Error bars represent the 90% confidence interval from bootstrap resampling. The number of forecasts is n.

For maximum surface wind (intensity) (Fig. 2), again, the EnKF analyses led to larger errors, while the WRF forecasts have large errors than the corresponding GFS forecasts. The latter again differs from the finding of Xue et al. (2013) for the 2010 hurricane season. The larger WRF errors appear to be due to over-intensification of tropical cyclones over time. The hypothesized reasons are threefold: (1) 127 out of the 178 forecasts were for tropical cyclones below hurricane strength for which GFS performed reasonably well; (2) other model forecasts in 2012 as well as NHC had a tendency to over-forecast intensity; (3) the WRF forecasts did not included ocean coupling, and (4) dry Saharan air contributed to the inhibition of tropical cyclone intensification, and the phenomenon was not well captured by the model. These are issues require further investigation.

2. Assimilation of satellite-derived winds and inner-core observations with hurricane Earl (2010)

For experiments assimilating rapid-scan satellite-derived winds, inner core airborne Doppler radar radial wind and dropsonde observations using EnKF for Hurricane Earl (2010), the Goddard Lin microphysics and MYJ PBL schemes were used. GFS ensemble forecasts are used to initialize a 40-member ensemble. The data in the inner-core region are assimilated in a 225 min window at 75-min intervals. Vr and dropsonde data are thinned and combined to create super-observations and spatially adjusted for TC movement before being assimilated. They and the satellite winds are assimilated with successive covariance localizations with different localization radii for different observation types. Ensemble spreads are maintained using adaptive covariance inflation and are consistent with observation innovations.

The assimilation of satellite-derived winds is found to improve the analysis of upper tropospheric winds more than at the mid- and lower troposphere, partly owing to the concentration of the data above 200 hPa.

The increments of winds and pressure from the assimilation of Vr and dropsondes in the first assimilation cycle are shown in Fig. 3. Assimilating Vr helps to build up a new vortex by inducing the cyclonic circulation and negative pressure increments of up to 6 hPa around the best track TC center (Fig. 3). The anticyclonic circulation and positive pressure increments around the background TC center indicate the weakening of the background vortex from the assimilation of Vr. The combined effect is the change of TC center toward the best track position. The wind and pressure increments from the assimilation of dropsonde winds and pressure have similar structures to assimilating Vr but with smaller magnitude. The assimilation of Vr and dropsonde observations also enhance the simulated TC warm core (not shown) by inducing positive increments of potential temperature around the best track TC center.

The inner core structure in the final analysis with Vr data (EXpVr) has stronger axisymmetric wind field and warm TC core than in experiment NODA without inner core DA (Fig. 4). The vortex is also deeper with a smaller maximum wind radius. The assimilation of dropsonde observations also improves the analysis: the vortex is stronger but shallower than ExpVr. The impact from the dropsonde observations is mostly below 3 km height (Fig. 4). Dropsonde winds and pressure have larger impacts than temperature and qv observations, while assimilating all dropsonde observation types shows the largest improvement than individual types. The assimilation of both Vr and dropsonde has similar impacts to the assimilation of Vr only, suggesting the impact from the large amount of airborne Vr can be dominant in the cloud-resolving TC analysis. The impacts on the warm core in the final analysis from various observation types are consistent with the wind fields.

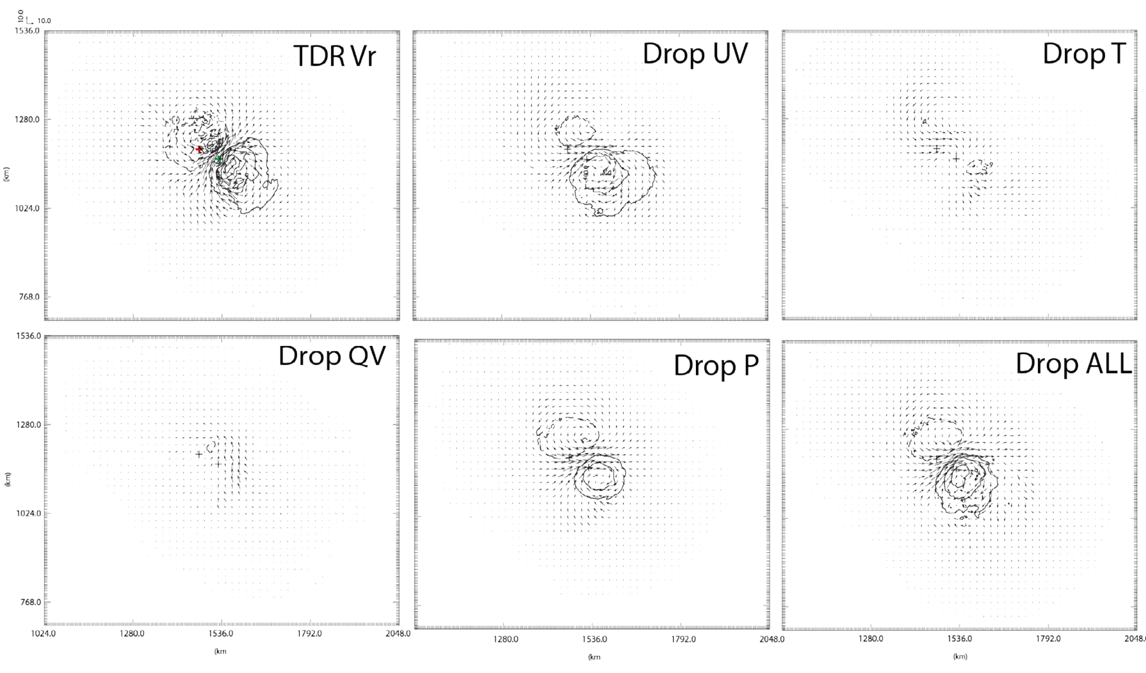

Fig. 6: Winds and pressure (contour every 1 hPa) increments at z = 2 km for different DA experiments in the first assimilation cycle.

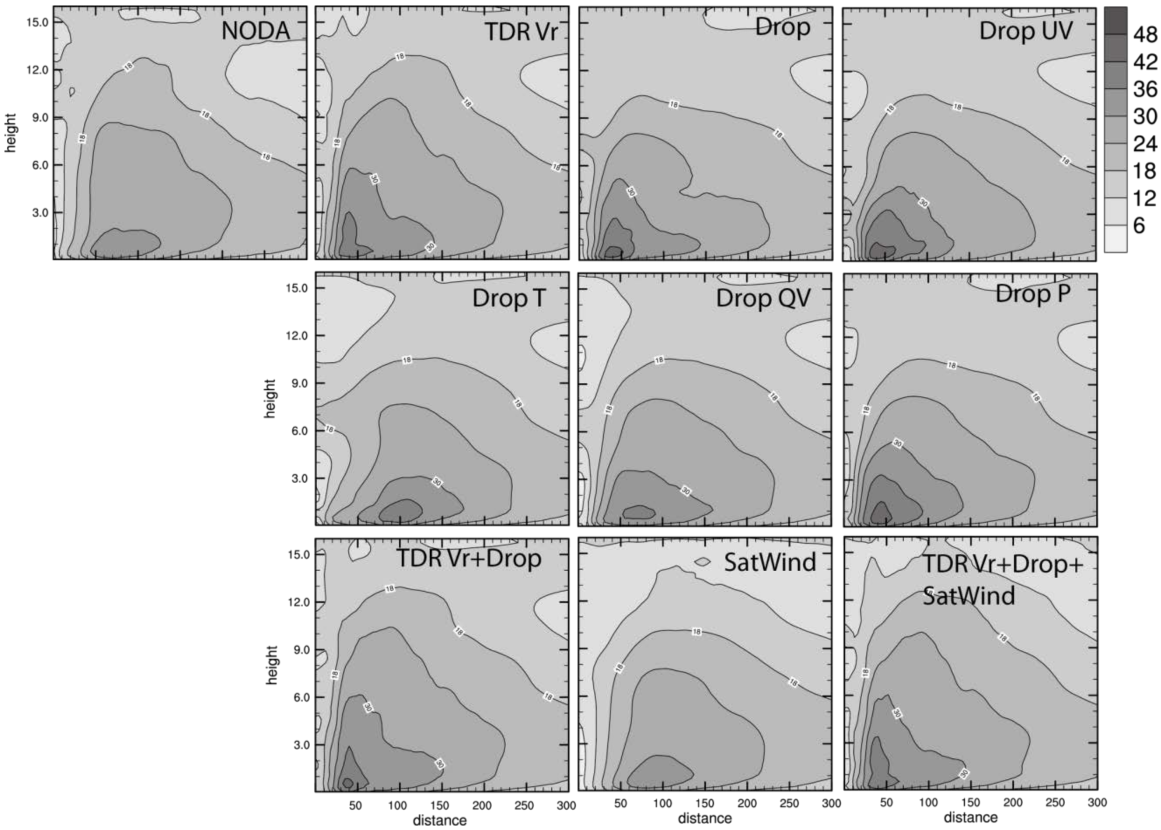

Fig. 7: Azimuthally averaged axisymmetric horizontal winds of the final analysis for different DA and NODA experiments.

A 36-hour forecast follows in each experiment. The forecast track is closer to the best track with the DA. The 36-hour mean track errors of DA experiments range from 82 (assimilating all three types) to 102 km (assimilating satellite winds only), smaller than the 123 km of NODA. The experiment assimilating all three types captures the intensification well during the first 21 hour (Fig. 5). The predicted MSLP of NODA is too weak during the first 15 hours of forecast. The experiment assimilating Vr alone produced the strongest TC in the first 24 hours. Among the experiments assimilating individual dropsonde observation types, dropsonde pressure and moisture lead to stronger intensity forecasts (Fig. 5). The maximum surface wind forecasts are generally consistent with MSLP except for an immediate spinning-down in the first 3 hours.

In summary, the assimilation of satellite-derived winds improves the track forecast of Earl through the improvement on the storm environment, especially at the upper troposphere. The assimilation of inner core airborne Vr and dropsonde observations improves the inner core vortex wind and warm core structure, leading to improved intensity and track forecasts.

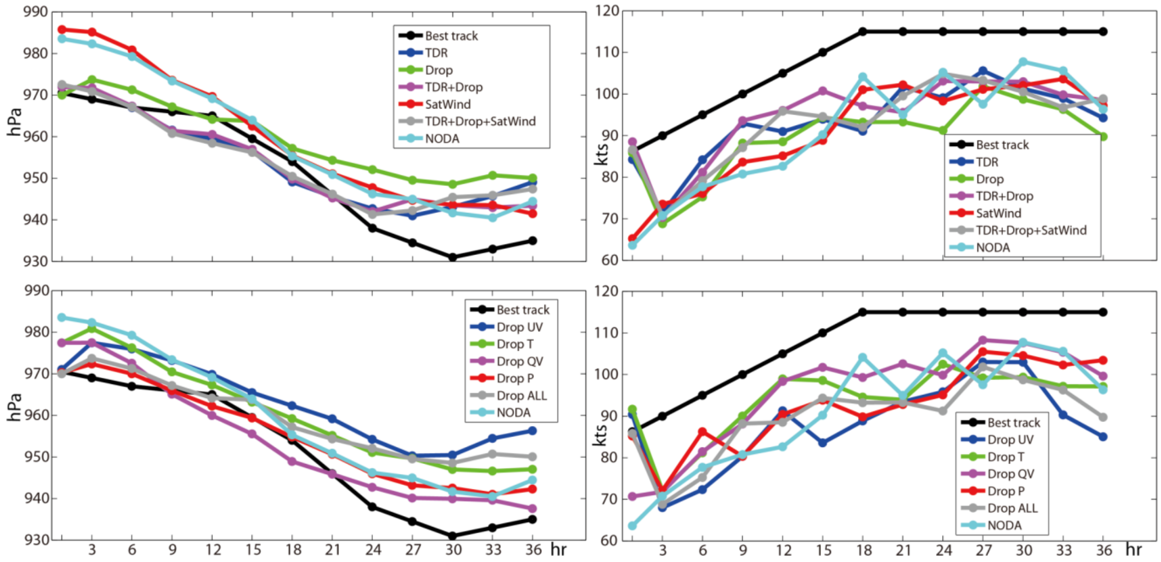

Fig. 8: Predicted minimum sea level pressures (left column) and maximum surface winds (right column) of 36 hours forecasts for different experiments.

IMPACT/APPLICATIONS

Codes developed by CAPS and testing data sets for COAMPS had been transferred back to the Naval Research Lab (NRL) at Moneterey, and close regular interactions occur with NRL scientists, including Dr. Yi Jin, who also visited CAPS for one week in 2013.

RELATED PROJECTS

ONR Defense EPSCOR program (N00014-10-1-0133): "Prediction and Predictability of Tropical Cyclones over Oceanic and Coastal Regions and Advanced Assimilation of Radar and Satellite Data for the Navy Coupled Ocean-Atmosphere Mesoscale Prediction System".

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